

PCT

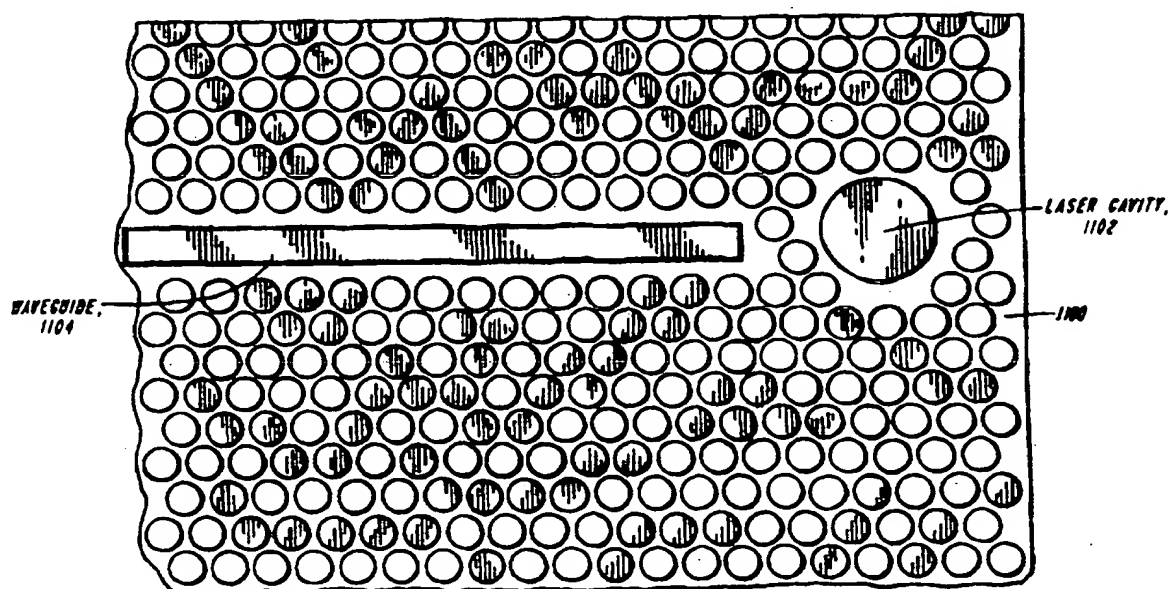
WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau



INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

<p>(51) International Patent Classification⁶ : H01S 3/085, G02B 6/12</p>	<p>A1</p>	<p>(11) International Publication Number: WO 96/27225 (43) International Publication Date: 6 September 1996 (06.09.96)</p>
<p>(21) International Application Number: PCT/US96/01903 (22) International Filing Date: 14 February 1996 (14.02.96) (30) Priority Data: 08/395,441 28 February 1995 (28.02.95) US (71) Applicant: MASSACHUSETTS INSTITUTE OF TECHNOLOGY [US/US]; 77 Massachusetts Avenue, Cambridge, MA 02139 (US). (72) Inventors: JOANNOPOULOS, John, D.; 64 Douglas Road, Belmont, MA 02178 (US). MEADE, Robert, D.; Apartment #2, 500 Dorian Road, Westfield, NJ 07090 (US). (74) Agents: CONNORS, Matthew, E. et al.; Samuels, Gauthier, Stevens & Reppert, Suite 3300, 225 Franklin Street, Boston, MA 02110 (US).</p>		<p>(81) Designated States: CA, JP, European patent (AT, BE, CH, DE, DK, ES, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE). Published <i>With international search report. Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.</i></p>

(54) Title: RESONANT CAVITIES EMPLOYING TWO-DIMENSIONAL PERIODIC DIELECTRIC MATERIALS



(57) Abstract

The present invention provides a resonant cavity including a planar two-dimensional periodic dielectric structure which exhibits a photonic band gap and a defect in the periodic dielectric structure which results in an electromagnetic mode within the photonic band gap. The photonic band gap effects an in-plane spacial confinement of electromagnetic radiation generated within the structure. The electromagnetic radiation is vertically confined by total internal reflection.

Best Available Copy

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AM	Armenia	GB	United Kingdom	MW	Malawi
AT	Austria	GE	Georgia	MX	Mexico
AU	Australia	GN	Guinea	NE	Niger
BB	Barbados	GR	Greece	NL	Netherlands
BE	Belgium	HU	Hungary	NO	Norway
BF	Burkina Faso	IE	Ireland	NZ	New Zealand
BG	Bulgaria	IT	Italy	PL	Poland
BJ	Benin	JP	Japan	PT	Portugal
BR	Brazil	KE	Kenya	RO	Romania
BY	Belarus	KG	Kyrgyzstan	RU	Russian Federation
CA	Canada	KP	Democratic People's Republic of Korea	SD	Sudan
CF	Central African Republic	KR	Republic of Korea	SE	Sweden
CG	Congo	KZ	Kazakhstan	SG	Singapore
CH	Switzerland	LI	Liechtenstein	SI	Slovenia
CI	Côte d'Ivoire	LK	Sri Lanka	SK	Slovakia
CM	Cameroon	LR	Liberia	SN	Senegal
CN	China	LT	Lithuania	SZ	Swaziland
CS	Czechoslovakia	LU	Luxembourg	TD	Chad
CZ	Czech Republic	LV	Latvia	TG	Togo
DE	Germany	MC	Monaco	TJ	Tajikistan
DK	Denmark	MD	Republic of Moldova	TT	Trinidad and Tobago
EE	Estonia	MG	Madagascar	UA	Ukraine
ES	Spain	ML	Mali	UG	Uganda
FI	Finland	MN	Mongolia	US	United States of America
FR	France	MR	Mauritania	UZ	Uzbekistan
GA	Gabon			VN	Viet Nam

- 1 -

**RESONANT CAVITIES EMPLOYING TWO-DIMENSIONAL
PERIODIC DIELECTRIC MATERIALS**

5 The invention is directed to resonant cavities employing two dimensional periodic dielectric materials.

 In the past decades, the semiconductor laser has come to play a critical role in numerous applications including optical information storage and retrieval (e.g. CD players),
10 lightwave communication (e.g. optical fibers), and computer input/output. In most commercial applications, these lasers have been of the buried heterostructure or distributed feed back (DFB) varieties. While lasers of this type have been tremendously successful, there have recently been attempts
15 at improving the design of semiconductor lasers to improve efficiency, power output, linewidth, modulation speeds and other device characteristics. In particular, there has been recent success at fabricating vertical cavity surface emitting lasers (VCSELs), microdisk lasers, and even steps
20 toward a photonic band gap (PBG) laser. In each of these systems, the gain is achieved in a similar manner, i.e. by injecting carriers across a p-n junction. However, in each system the cavity in which the lasing occurs is created in a different manner.

25 In order to put the cavity of the present invention in perspective, it is beneficial to discuss the three conventional cavities which are part of the state of the art. All of the aforementioned cavities have a common feature in that a cavity must have walls along each
30 dimension which reflect electromagnetic radiation. There are two principle ways to reflect light at optical frequencies, total internal reflection (TIR) and reflection from a periodic dielectric structure.

 TIR occurs at the interface between two dielectrics
35 when it is not possible to simultaneously match both the frequency and the phase on both sides of the interface. When light is incident from the high dielectric material, it is totally reflected back into the material. This only occurs if the angle of incidence is greater than the

- 2 -

critical angle. Light can also be reflected at the interface between a homogeneous dielectric and a periodic dielectric. This occurs when multiple scattered waves in the periodic medium destructively interfere, thereby
5 prohibiting propagation inside the periodic medium.

When a periodic medium forbids the propagation of light, it is said to have a photonic band gap (PBG). It is possible to make PBG structures which reflect light along a single axis (a multilayer film) as described in U.S. Pat.
10 App. Ser. No. 08/318,161 entitled "Resonant Microcavities Employing One-Dimensional Periodic Dielectric Waveguides", incorporated herein by reference. It is also possible to make PBG structures which reflect light incident from any arbitrary direction (3-D PBG), as described in U.S. Pat.
15 App. Ser. No. 08/240,916 entitled "Three-Dimensional Periodic Dielectric Structures Having Photonic Bandgaps", also incorporated herein by reference. The present invention relates to PBG structures which reflect light incident in a single plane, thus a two-dimensional PBG.

20 Having identified the two ways to reflect light, it is now possible to review the conventional cavities which are used in semiconductor lasers according to a simple scheme. These cavities are labeled according to how light is reflected along each of the three axes. Consider, for
25 example, microdisk laser 100 shown in Fig. 1. The microdisk is made of a small high-index disk 102 having a gain medium which is made of one or several quantum layers in the center of the disk. The dominant resonant (high-Q) mode 104 is called a whispering-gallery mode since it propagates around
30 the edge of the disk with low losses due to total internal reflection. In this case, the light is totally internally reflected along every axis, and so it is designated T3.

The situation is changed when we consider the VCSEL structure 200 of Fig. 2 (or, equivalently, a DFB laser with
35 phase slip). The VCSEL is made of two multilayer dielectric quarter-wave mirrors 202, 204 separated by a cavity 206 having a gain medium of one or several quantum wells. These periodic dielectrics reflect light incident normal to the

- 3 -

layers, in the vertical direction. Along the other two directions light is guided along the dielectric-air boundary by TIR and so this construction is labeled as P1T2. In spite of the advantages of the VCSEL over typical 5 semiconductor lasers, the most significant drawback of these devices is their vertical position and vertical emission 208 on the substrate which limits significantly their usefulness in optoelectronic integrated circuits (OEICs).

In Fig. 3, a resonant cavity constructed in a three- 10 dimensional periodic dielectric structure 300 with PBG is shown. This cavity is surrounded by a dielectric crystal which is periodic along all three directions, thus the periodicity reflects light along all three directions. Such a structure is labeled P3. U.S. 5,187,461 entitled "Low- 15 loss Dielectric Resonator Having a Lattice Structure With a Resonant Defect", incorporated herein by reference, describes a three-dimensional dielectric lattice with a defect.

It is therefore an object of the present invention to 20 provide a new technique of producing high Q resonant cavities. These cavities may be employed in a laser, as filters, or in any other application which requires a resonant cavity.

It is a further object of the present invention to 25 provide a resonant cavity which achieves in-plane (x-y) localization of electromagnetic radiation using a two-dimensional periodic dielectric, and vertical confinement of electromagnetic radiation using TIR. Such a cavity is designated as P2T1 and will work at any frequency between 30 ultraviolet and microwave.

SUMMARY OF THE INVENTION

The present invention provides a resonant cavity including a planar two-dimensional periodic dielectric 35 structure and a defect in the periodic dielectric structure which results in a photonic band gap. The photonic band gap effects an in-plane spacial confinement of electromagnetic radiation generated within the structure. The

- 4 -

electromagnetic radiation is vertically confined by total internal reflection.

BRIEF DESCRIPTION OF THE DRAWINGS

5 Fig. 1 shows a prior art microdisk resonant cavity in block diagram form;

 Fig. 2 shows a prior art vertical cavity surface emitting resonant cavity in block diagram form;

 Fig. 3 shows a prior art resonant cavity constructed in
10 a three-dimensional periodic dielectric structure with PBG in block diagram form;

 Figs. 4A and 4B respectively show in block diagram form a resonant cavity constructed in a two-dimensional periodic dielectric structure with a defect and a waveguide in
15 accordance with the present invention;

 Fig. 5 shows an exemplary embodiment of a resonant cavity configured in a two-dimensional periodic dielectric structure;

 Fig. 6 shows a second exemplary embodiment of a
20 resonant cavity configured in a two-dimensional periodic dielectric structure;

 Fig. 7 shows a third exemplary embodiment of a resonant cavity configured in a two-dimensional periodic dielectric structure;

25 Figs. 8A and 8B respectively show a schematic of a cavity with a surrounding periodic lattice and a contour plot of associated electric fields of the cavity mode; Fig. 8C shows a plot of cavity mode frequency as defect radius changes;

30 Fig. 9 shows a plot of the effective index of a guided wave versus the width of the guiding layer;

 Figs. 10A-10C show schematic plots of electric field intensity for modes with zero, one and two nodes;

 Fig. 11 shows an exemplary construction of a laser
35 cavity configured within a two-dimensional periodic dielectric structure proximate to an integrated waveguide; and

 Fig. 12 shows a two-dimensional periodic dielectric

- 5 -

structure having a resonant cavity in close proximity to an input waveguide for use as a semiconductor filter in accordance with the present invention.

5 DETAILED DESCRIPTION OF THE ILLUSTRATED EMBODIMENTS

With reference now to Fig. 4A, a high Q resonant cavity 400 in accordance with the present invention is shown schematically in block diagram form. The cavity 400 is constructed in a two-dimensional periodic dielectric 10 structure 402 having a PBG. As is known in the art, the existence of a PBG results in a range of frequencies where electromagnetic energy is not permitted to exist in the periodic structure. A defect 404 introduced to the structure results in the structure exhibiting an 15 electromagnetic mode within the PBG. Since the mode is not normally allowed within the PBG, the mode exists only localized to the defect. In accordance with the present invention, the mode is confined because the dielectric structure is periodic along two directions, and so it can 20 reflect light if it is propagating in the plane of the underlying substrate. Moreover, the mode is also confined in the vertical direction by TIR. Accordingly, this cavity is classified as P2T1.

It is understood that the energy developed within the 25 cavity is captured within the cavity. However, the energy leaks out exponentially from the cavity with respect to distance to the cavity. In other words, there is an exponential decay of intensity of the mode into the surrounding regions of the cavity. Accordingly, it is 30 desirable to recapture this escaped energy. If a waveguide is positioned in the vicinity of the cavity, the energy can be recaptured and channeled through the waveguide. Fig. 4B shows a periodic structure with an integrated waveguide 406 which can be used to couple energy out of the cavity. As 35 will be discussed hereinafter, it will be desirable to couple into the cavity using a waveguide in close proximity to the defect. Under these circumstances, the waveguide is a linear defect in an otherwise periodic dielectric

- 6 -

structure.

The 2D PBG cavity of the present invention has the two important features of in-plane confinement of light employing a two-dimensional photonic band gap material, and 5 vertical confinement of light via TIR. Each of these features will be discussed in detail hereinafter.

According to the present invention, the in-plane confinement of electromagnetic radiation is achieved employing a two-dimensional periodic dielectric array. Such 10 a structure can be produced with a photonic band gap, which reflects light from all in-plane directions. In particular, square, triangular and honeycomb lattices have adequate electromagnetic properties. Moreover, such dielectric arrays may be constructed, for example, either from air in 15 dielectric as achieved by resonant cavity 500 of Fig. 5, or dielectric in air as achieved by resonant cavities 600 and 700 of Figs. 6 and 7, respectively. It will be appreciated by those of skill in the art that other configurations of dielectric arrays are possible without the use of air, in 20 particular it is desirable to obtain a structure with sufficient dielectric contrasts. While the subject of two dimensional dielectric lattices has received some attention as reflected in Meade et al., "Novel Applications of Photonic Band Gap Materials: Low-loss Bends and High Q 25 Cavities", incorporated herein by reference, however, in accordance with the present invention, the electromagnetic energy is vertically confined by TIR in a 2D PBG structure.

Having created a reflecting two-dimensional dielectric lattice, it is then necessary to embed a defect in this 30 lattice to localize the light. This process is similar in spirit to that described in U.S. 5,187,461 entitled "Low-loss Dielectric Resonator Having a Lattice Structure With a Resonant Defect", incorporated herein by reference, in which a three-dimensional dielectric lattice is created and a 35 defect introduced. In accordance with the present invention, the 2D periodicity is responsible for 2D (in-plane) localization. For example, with reference to Figs. 8A and 8B, a localized mode created by a cavity 800

- 7 -

surrounded by 2D reflecting walls is shown. In Fig. 8A, the cavity is centrally located with a surrounding periodic lattice 802 of reflecting dielectric. The electric fields 804 associated with the localized cavity mode are shown in the contour plot of Fig. 8B. As in the 3D PGP structure, by varying the defect size the cavity resonance can be tuned to any frequency in the band gap, as shown in the plot of Fig. 8C.

In accordance with the present invention, the vertical confinement of electromagnetic radiation is achieved by creating a high dielectric layer surrounded by layers of lower dielectric constant. With reference back to Fig. 5, one exemplary embodiment of this implementation is shown. The resonant cavity structure 500 includes a layer of material 502 having a predetermined dielectric constant with a periodic array of air holes 504 disposed therethrough. The cavity is formed by breaking the perfect periodicity along the x and y axes, hence forming a local defect 506 which can lead to strong spacial confinement of the radiation around the defect in order to generate an electromagnetic mode. In this embodiment, the TIR occurs between the dielectric material and air on both sides of the cavity.

A straightforward way to produce the cavity 500 at microwave frequencies is to take a plane of high dielectric material and drill the periodic series of holes with conventional machine tools, thus resulting in the 2D PBG structure. At optical frequencies, such a cavity can be fabricated employing techniques similar to those used to fabricate the microdisk laser. For example, photolithography, x-ray lithography, electron beam lithography, and reactive ion beam etching.

Another exemplary embodiment of a P2T1 cavity 600 is shown in Fig. 6. In this embodiment, a layer 602 of high index material such as GaAs is grown on a low index substrate 604, such as GaAlAs. Thereafter, a periodic series of columns, for example, are formed by etching. A defect 606 is provided at a selected position. The defect

- 8 -

is formed, for example, by removing the high index material from a selected column or any other process which would interrupt the periodicity of the surrounding material. The column structures are produced, for example, by utilizing
5 reactive ion beam etching or electron beam lithography. At the top surface, the index contrast between the GaAs and air is large and so the reflections are quite strong, while at the bottom surface the index contrast between the GaAs and GaAlAs is small, thus the reflections are weaker.

10 A further exemplary embodiment of a resonant cavity 700 which achieves inplane confinement of electromagnetic radiation is shown in Fig. 7. The cavity 700 includes a high index layer 702 of, for example, GaAs, positioned between lower index material layers 704, 705 such as GaAlAs.
15 Through conventional chemical etching, a periodic array of columns are formed. The defect 706 which breaks the periodicity of the structure in the illustrated example is formed by the creation of an oversized column.

In this embodiment, light is confined to the high index
20 GaAs layer surrounded by low index GaAs on either side. It will be appreciated by those of skill in the art that while the illustrated embodiments are shown utilizing GaAs/GaAlAs epilayers, in fact any two dielectric materials of differing dielectric constant can be used. For example, an
25 alternative construction can include a layer of GaInAsP between layers of InP.

One important aspect of designing a P2T1 cavity in accordance with the present invention is the choice of width of the high dielectric layer, which must be neither too
30 large nor too small. For a laser application, the vertical mode profile at a given frequency ω_0 (the frequency of the cavity mode which is chosen to be the frequency of the laser light) is of the greatest interest. In particular, the dependence of the vertical mode profile with the width of
35 the layer in order to determine the number of guided modes is of interest. This dependence is shown in the graph of Fig. 9, which plots the effective index, $n_{eff} = k/\omega_0$, versus layer width, where k is the wave vector of the propagating

- 9 -

mode. This graph shows that there are a number of critical widths $w_{c,n}$ above which a mode with n nodes becomes guided (solid lines) and below which the mode is a resonance (dashed-dotted lines). To create a high-Q cavity, it is important to have exactly one guided mode. If there are no guided modes then there is no high-Q cavity mode. However, if there are several guided modes then there will be several high-Q cavities which may have similar frequencies. Therefore, it is necessary to choose the layer width $w_{c,0} < w < w_{c,1}$. Although the illustrated embodiments are considered with respect to only the simple case of a single layer of high dielectric material in the absence of the 2D PBG, the variation with width has the same qualitative behavior when the 2D PBG is accounted for. Figs. 10A-10C respectively show electric field intensity schematics for modes with zero, one and two nodes.

Another important aspect of designing a P2T1 cavity in accordance with the present invention is the proper consideration of polarization effects. For simplicity, the difference between polarizations in the description of layer widths is ignored. In fact, the critical widths $w_{c,n}$ of a single layer of high dielectric material is slightly different for TE (E-field parallel to the surface of the substrate) and TM (H-field parallel to the surface of the substrate) modes. This difference is magnified by the presence of the 2D PBG because in this case, the TE and TM modes have very different propagation properties. However, polarization considerations can be dealt with easily by choosing a 2D periodic lattice which has a gap only for either TE or TM modes.

One exemplary application of the resonant cavity of the present invention is for the production of semiconductor lasers. The 2D laser geometry is particularly useful for integrated optoelectronics. The utility arises from the ease of coupling the laser light into a nearby inplane waveguide as schematically shown in Fig. 11. Fig. 11 shows a two-dimensional periodic dielectric structure 1100 having laser cavity 1102 in close proximity to a waveguide 1104.

- 10 -

Because the dielectric is reflecting, the principle exit port for the electromagnetic radiation is into the waveguide. This configuration eliminates substrate radiation as a source of loss.

5 Another exemplary application of the resonant cavity of the present invention is for use in semiconductor device filters. The 2D geometry is also particularly useful for integrated optoelectronics. The utility similarly arises from the ease of coupling electromagnetic energy into and
10 out of a resonant cavity as schematically shown in Fig. 12. Fig. 12 shows a two-dimensional periodic dielectric structure 1200 having a resonant cavity 1202 in close proximity to an input waveguide 1204. Accordingly, electromagnetic energy can be transported to the resonant
15 cavity to induce the generation of further electromagnetic energy. Thereafter, because the dielectric is reflecting, the principle exit port for the electromagnetic radiation generated by the cavity is into an output waveguide 1206. This configuration can operate as a filter by designing the
20 cavity to include a defect which creates a desired electromagnetic mode, thus only specified portions of the generated electromagnetic energy are allowed to pass through to the output waveguide. It will be appreciated that the embodiment of Fig. 12 can be modified to include one or more
25 input waveguides as well as one or more output waveguides, depending on the desired filtering operation.

The foregoing description has been set forth to illustrate the invention and is not intended to be limiting. Since modifications of the described embodiments
30 incorporating the spirit and substance of the invention may occur to persons skilled in the art, the scope of the invention should be limited solely with reference to the appended claims and equivalents thereof.

35 What is claimed is:

- 11 -

CLAIMS

- 1 1. A resonant cavity comprising:
2 a planar two-dimensional periodic dielectric structure
3 which exhibits a photonic band gap; and
4 a defect in said periodic dielectric structure which
5 results in an electromagnetic mode localized around said
6 defect within said photonic band gap, wherein
7 said photonic band gap effects an in-plane spacial
8 confinement of electromagnetic radiation generated within
9 said structure, said electromagnetic radiation being
10 vertically confined by total internal reflection.
- 1 2. The resonant cavity of claim 1, wherein a waveguide
2 is provided within said two-dimensional periodic dielectric
3 structure in the proximity of said defect.
- 1 3. The resonant cavity of claim 2, wherein said
2 waveguide is supported by a substrate, said substrate
3 providing a refractive index contrast with said waveguide.
- 1 4. The resonant cavity of claim 1, wherein said
2 structure comprises a two-dimensional array of holes
3 provided therein for periodicity.
- 1 5. The resonant cavity of claim 4, wherein said local
2 defect comprises a region in which at least one of said
3 holes is varied in size with respect to the remaining holes
4 in said array.
- 1 6. The resonant cavity of claim 1, wherein said
2 structure comprises an array of rods extending therefrom for
3 periodicity.
- 1 7. The microcavity of claim 6, wherein said defect
2 comprises a region in which at least one of said rods is
3 varied in size or dielectric constant with respect to the
4 remaining rods in said array.

- 12 -

5 8. The resonant cavity of claim 7, wherein each of
6 said array of rods includes a first portion comprising a
7 material having a first dielectric constant and a second
8 portion comprising a material having a differing second
9 dielectric constant.

1 9. A resonant cavity which exhibits an electromagnetic
2 mode for use in a microlaser, comprising:

3 a planar two-dimensional periodic dielectric structure
4 which exhibits a photonic band gap and vertically confines
5 radiation generated therewithin by total internal
6 reflection; and

7 a local defect disposed in said periodic dielectric
8 structure which results in an electromagnetic mode localized
9 around said defect, said local defect accommodating an in-
10 plane spacial confinement of said radiation.

1 10. The microcavity of claim 9, wherein a waveguide is
2 provided within said two-dimensional periodic dielectric
3 structure in the proximity to said defect.

1 11. The resonant cavity of claim 10, wherein said
2 waveguide is supported by a substrate, said substrate
3 providing a refractive index contrast with said waveguide.

1 12. The microcavity of claim 9, wherein said structure
2 comprises an array of holes provided therein for
3 periodicity.

1 13. The microcavity of claim 12, wherein said defect
2 comprises a region in which at least one of said holes is
3 varied in size with respect to the remaining holes in said
4 array.

1 14. The microcavity of claim 9, wherein said structure
2 comprises an array of rods extending therefrom for
3 periodicity.

- 13 -

1 15. The microcavity of claim 14, wherein said defect
2 comprises a region in which at least one of said rods is
3 varied in size or dielectric constant with respect to the
4 remaining rods in said array.

1 16. The resonant cavity of claim 15, wherein each of
2 said array of rods includes a first portion comprising a
3 material having a first dielectric constant and a second
4 portion comprising a material having a differing second
5 dielectric constant.

1 17. A method of producing a resonant cavity with
2 enhanced radiation confinement, comprising:
3 providing a substrate;
4 forming a planar two-dimensional periodic dielectric
5 structure which exhibits a photonic band gap on said
6 substrate, said photonic band gap effecting an in-plane
7 spacial confinement of electromagnetic radiation generated
8 within said structure, said electromagnetic radiation being
9 vertically confined by total internal reflection ; and
10 forming a defect in said periodic structure which
11 results in an electromagnetic mode within said photonic band
12 gap, and which accommodates spacial confinement of radiation
13 generated within said structure.

1 18. A device comprising:
2 a resonant cavity including a planar two-dimensional
3 periodic dielectric structure which exhibits a photonic band
4 gap, and a defect in said periodic dielectric structure
5 which results in an electromagnetic mode localized around
6 said defect within said photonic band gap, wherein said
7 photonic band gap effects an in-plane spacial confinement of
8 electromagnetic radiation generated within said structure,
9 said electromagnetic radiation being vertically confined by
10 total internal reflection; and
11 a waveguide integrated within said two-dimensional
12 periodic dielectric structure in the proximity of said
13 defect, said waveguide serving to channel portions of said

- 14 -

14 electromagnetic radiation generated by said resonant cavity.

1 19. The device of claim 18, wherein at least one
2 additional waveguide is integrated within said two-
3 dimensional structure in the proximity of said defect.

1 20. A resonant cavity device for use in a filter,
2 comprising:

3 a resonant cavity including a planar two-dimensional
4 periodic dielectric structure which exhibits a photonic band
5 gap, and a defect in said periodic dielectric structure
6 which results in an electromagnetic mode localized around
7 said defect within said photonic band gap, wherein said
8 photonic band gap effects an in-plane spacial confinement of
9 electromagnetic radiation generated within said structure,
10 said electromagnetic radiation being vertically confined by
11 total internal reflection; and

12 a first waveguide integrated within said two-
13 dimensional periodic dielectric structure in the proximity
14 of said defect, said first waveguide serving to channel
15 portions of said electromagnetic radiation generated by said
16 resonant cavity; and

17 a second waveguide integrated within said two-
18 dimensional periodic dielectric structure in the proximity
19 of said defect, said second waveguide serving to channel
20 electromagnetic radiation into said resonant cavity.

1/7

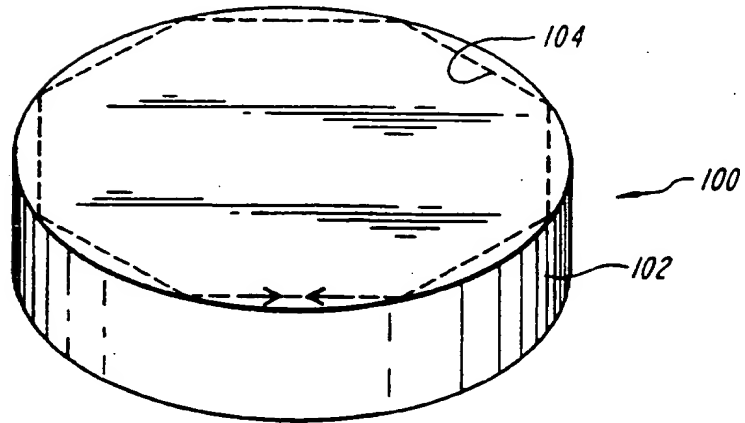


FIG. 1

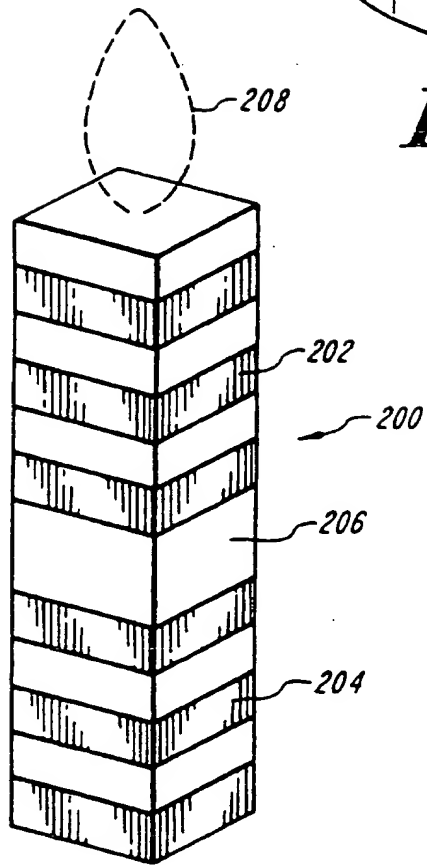


FIG. 2

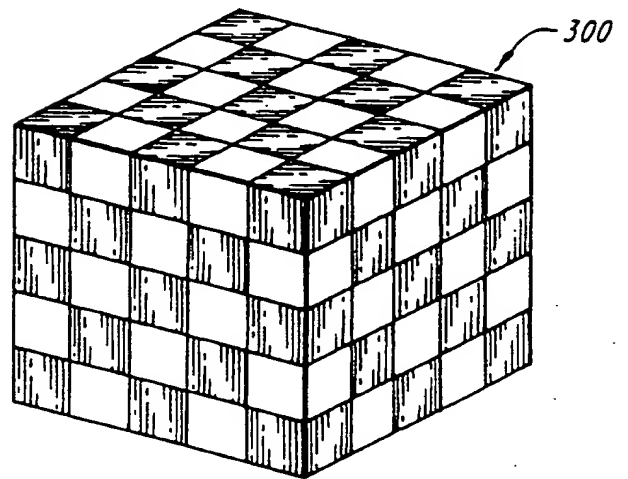


FIG. 3

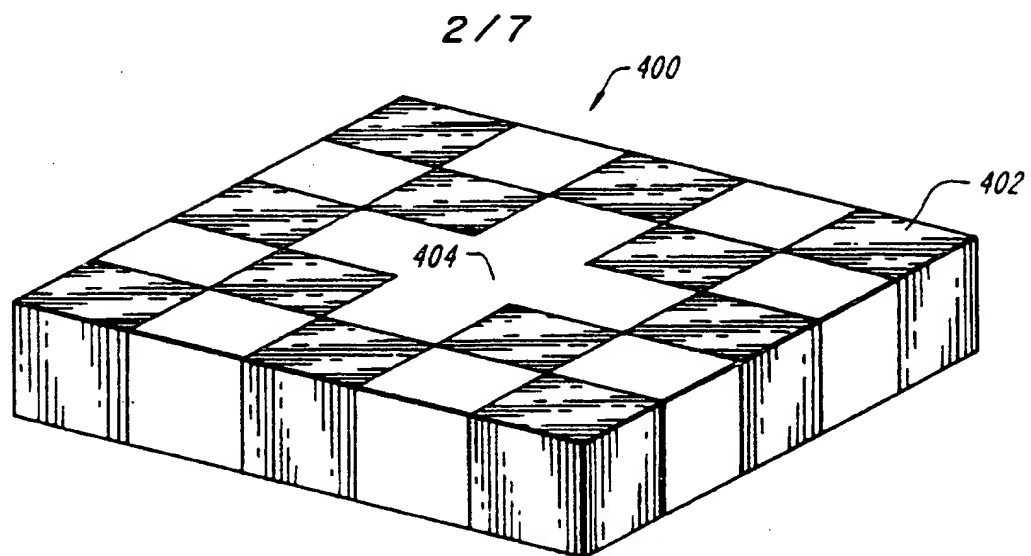


FIG. 4A

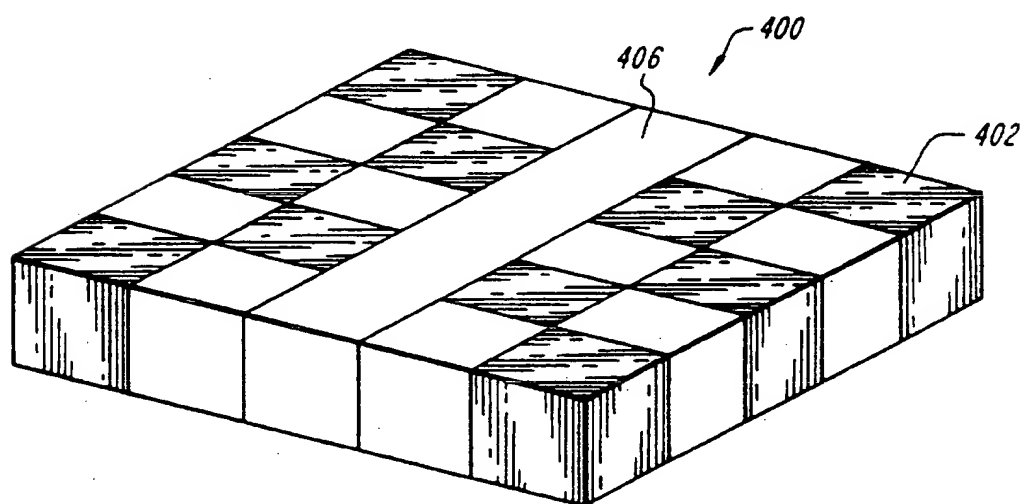
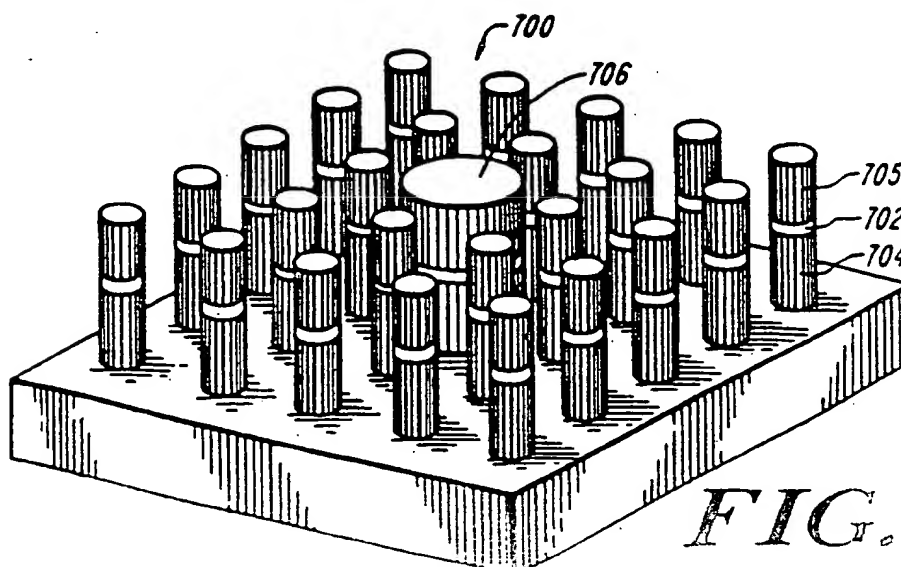
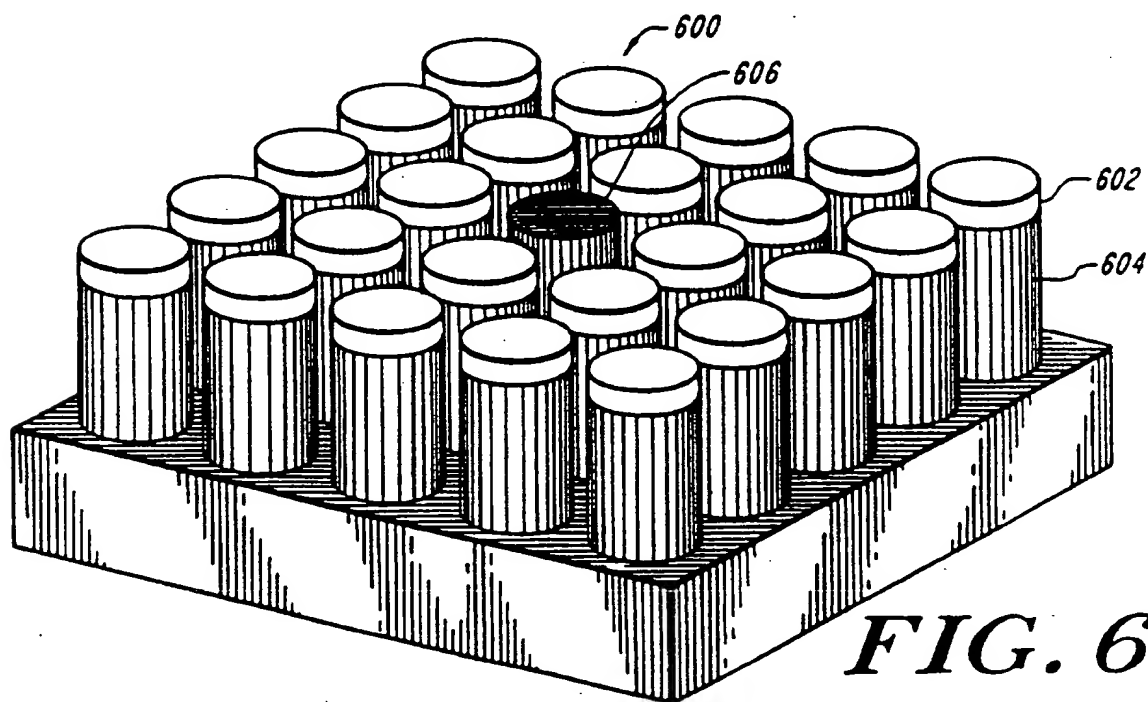
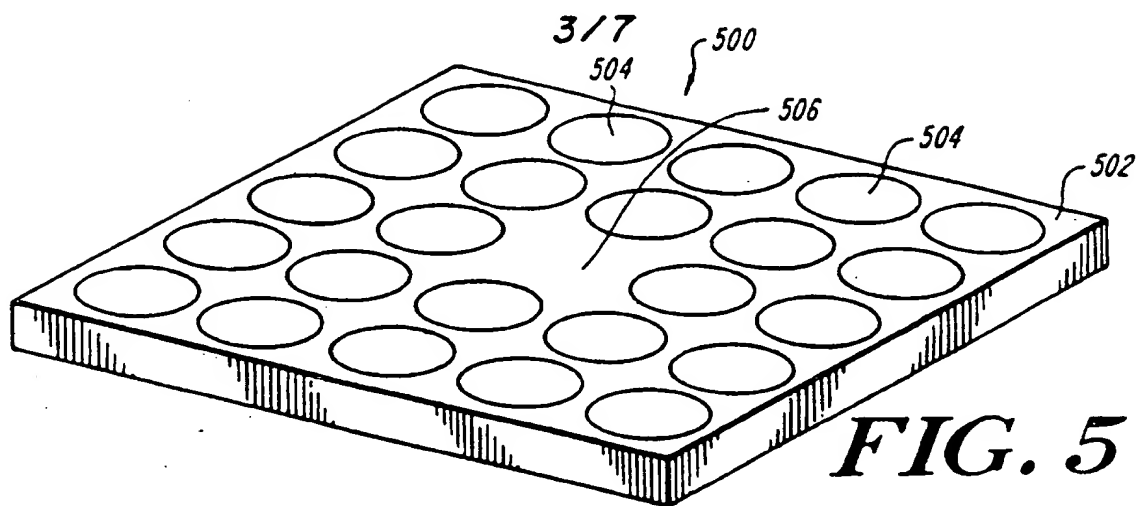
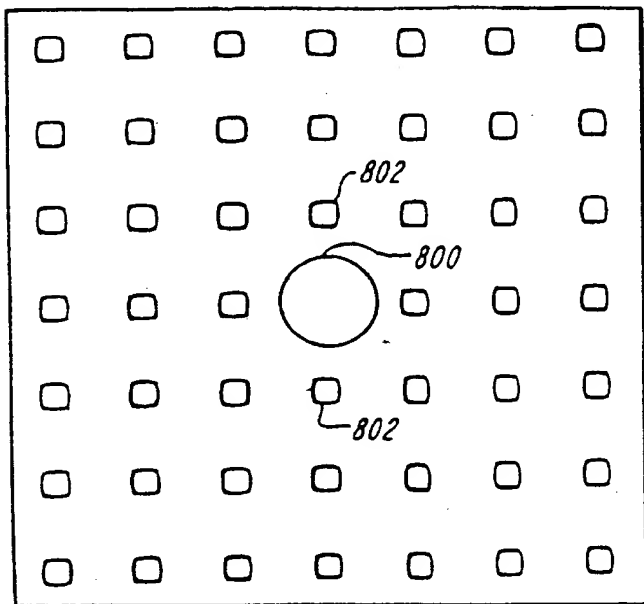
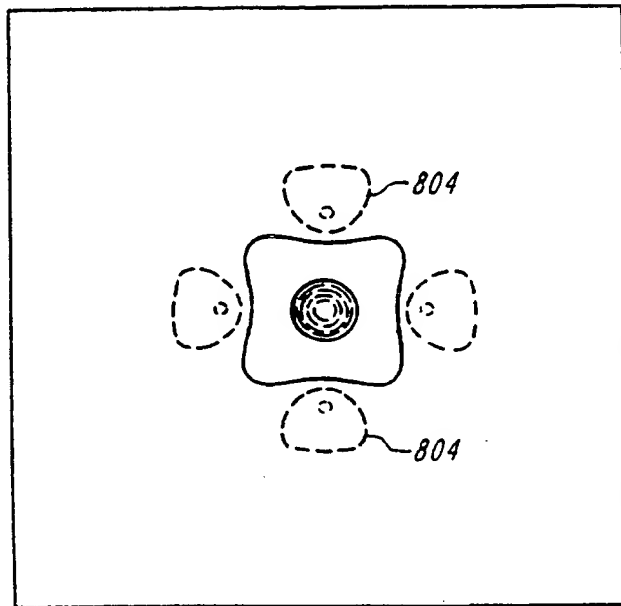
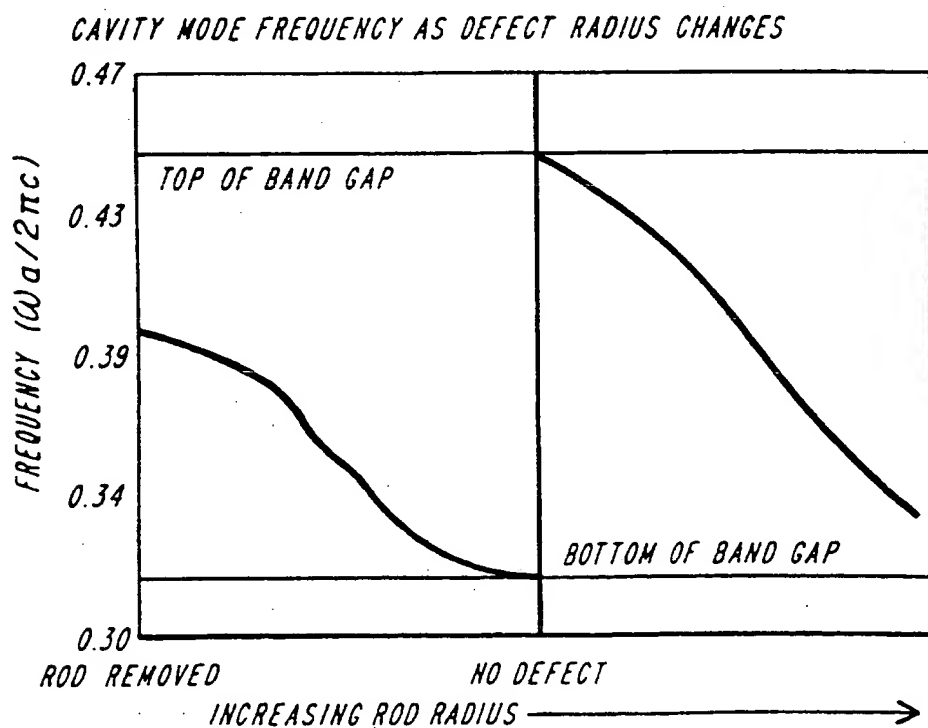


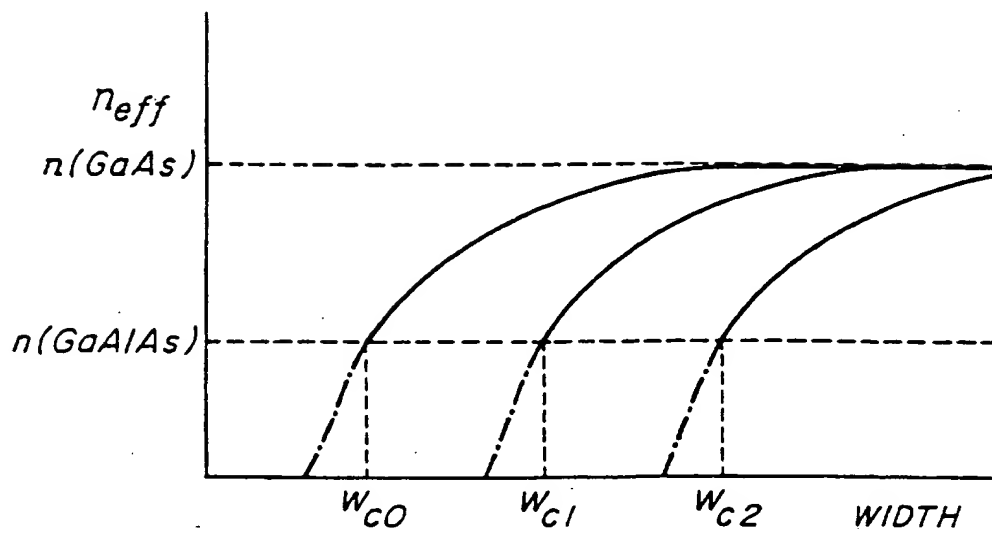
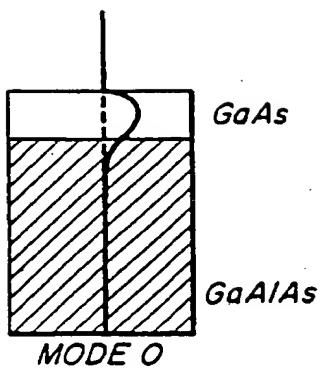
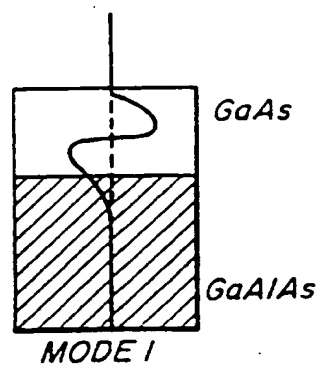
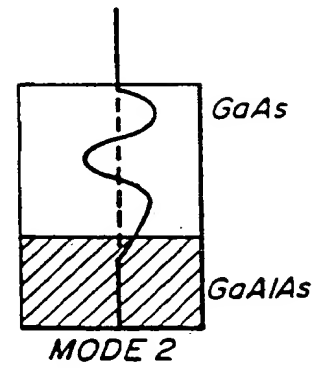
FIG. 4B



4/7

**FIG. 8A****FIG. 8B****FIG. 8C**

5/7

**FIG. 9****FIG. 10A****FIG. 10B****FIG. 10C**

6 / 7

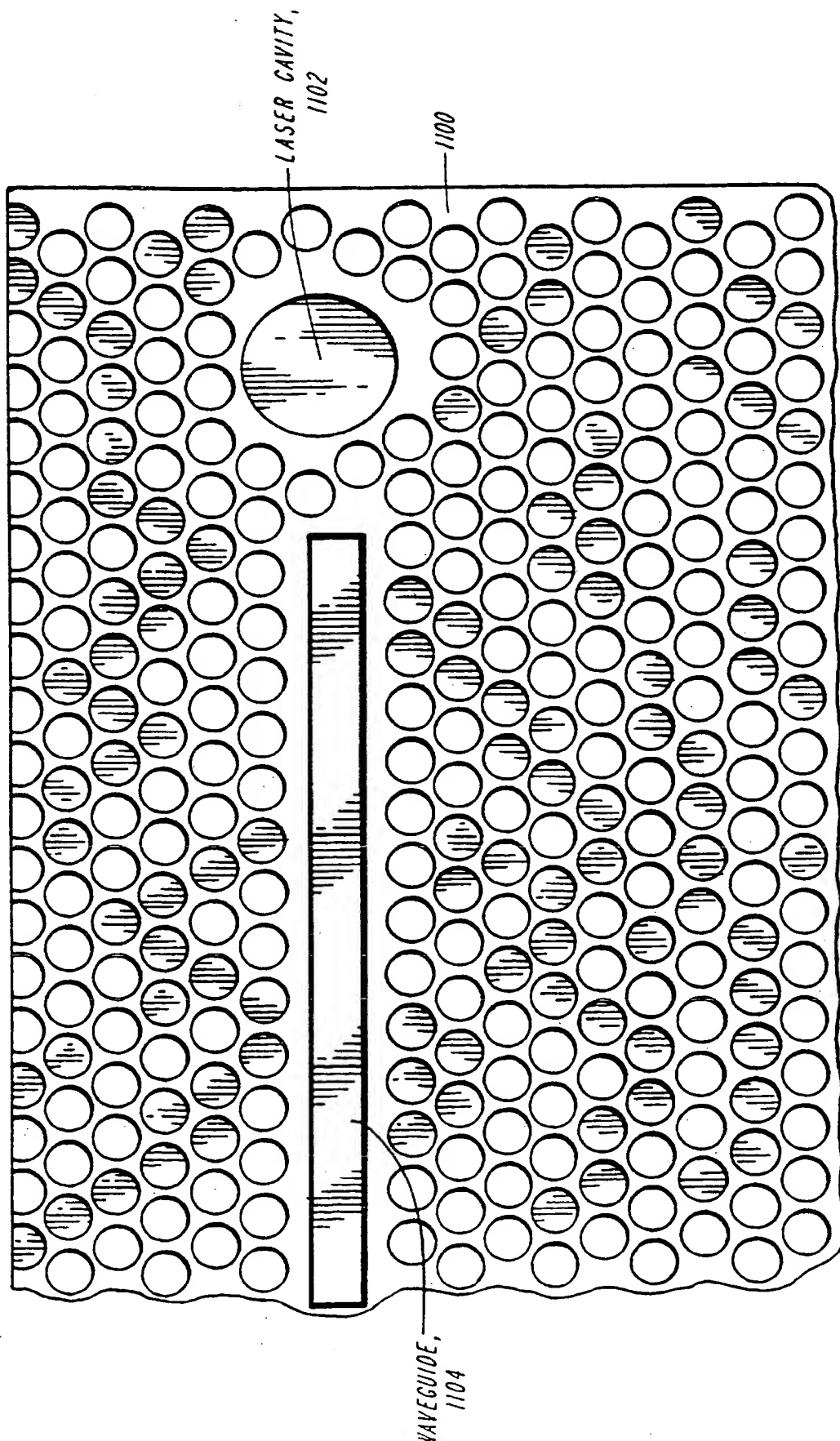


FIG. 11

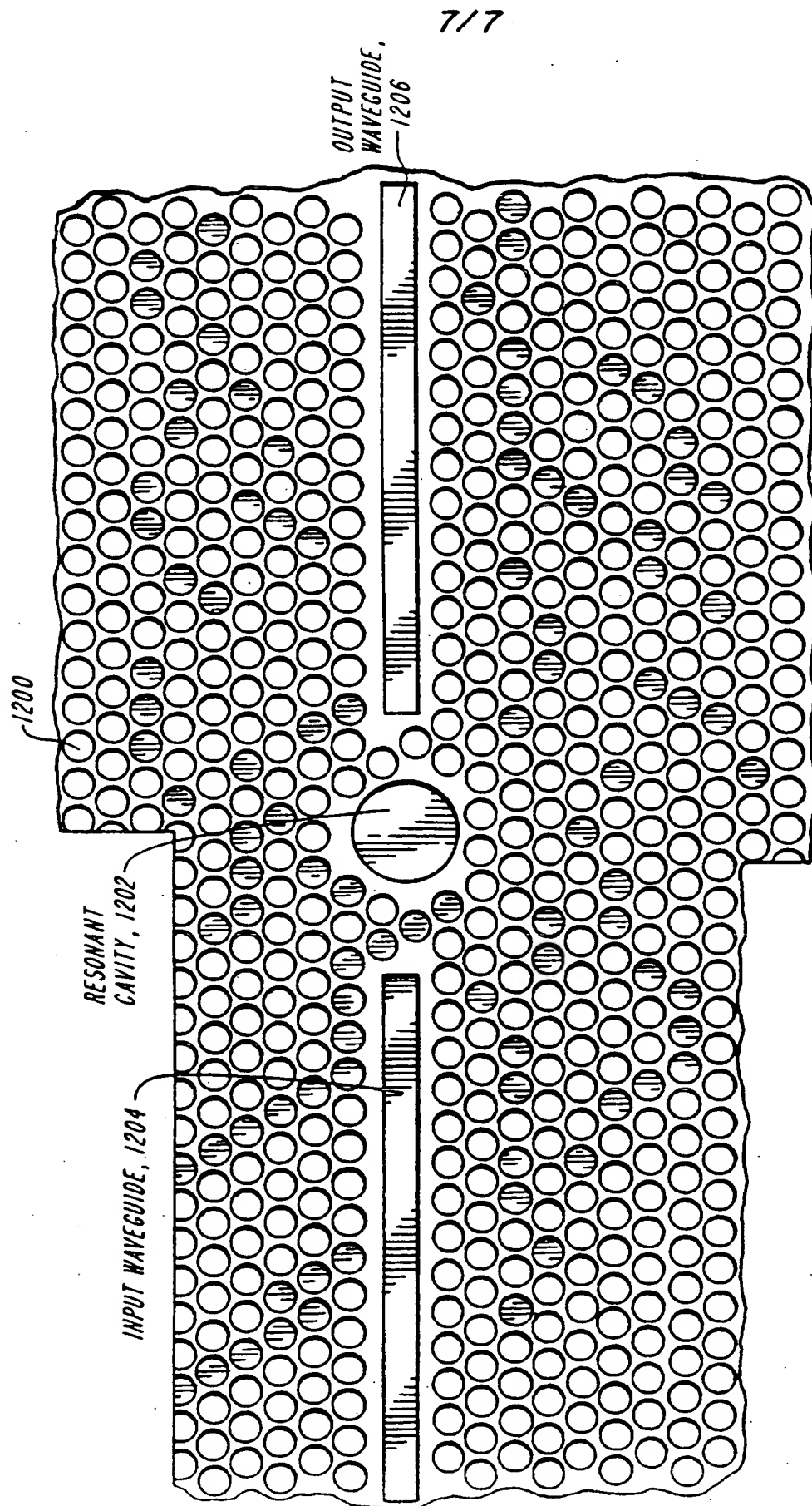


FIG. 12

INTERNATIONAL SEARCH REPORT

International Application No.
PCT/US 96/01903

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01S3/085 G02B6/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01S G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	SEMICONDUCTOR SCIENCE AND TECHNOLOGY, vol. 9, no. 8, August 1994, LONDON GB, pages 1493-1499, XP000572606 V. BERGER: "Three-level laser based on intersubband transitions in asymmetric quantum wells: a theoretical study"	1,4,5,9, 12,13,17
Y	see page 1496, right-hand column; figure 4E	1-3,10, 11,18-20
Y	US,A,5 187 461 (BROMMER KARL ET AL) 16 February 1993 cited in the application see column 5, line 9 - line 54; figures 5-9	1-3,10, 11,18-20

☒ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

* Special categories of cited documents:

- *A* document defining the general state of the art which is not considered to be of particular relevance
- *E* earlier document but published on or after the international filing date
- *L* document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
- *O* document referring to an oral disclosure, use, exhibition or other means
- *P* document published prior to the international filing date but later than the priority date claimed

- *T* later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
- *X* document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
- *Y* document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
- *&* document member of the same patent family

Date of the actual completion of the international search

17 June 1996

Date of mailing of the international search report

29.06.96

Name and mailing address of the ISA

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+ 31-70) 340-2040, Tx. 31 651 epo nl,
Fax (+ 31-70) 340-3016

Authorized officer

Claessen, L

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 96/01903

C(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	JOURNAL OF APPLIED PHYSICS, vol. 75, no. 9, 1 May 1994, NEW YORK US, pages 4753-4755, XP000562393 R.D. MEADE ET AL: "Novel applications of photonic band gap materials: Low loss bends and high Q cavities" cited in the application	1,6-9, 14-17
A	see figure 1C	4,5,9, 12,18,20
A	--- WO,A,94 16345 (MASSACHUSETTS INST TECHNOLOGY) 21 July 1994 see the whole document	1-3, 9-11, 18-20
A	--- PHYSICAL REVIEW A, vol. 48, no. 3, September 1993, NEW YORK US, pages 2246-2250, XP002005646 R.P STANLEY ET AL: "Impurity modes in one dimensional periodic systems: The Transition from photonic band gaps to microcavities" see page 2248, left-hand column, paragraph 2	1,9,17, 18
A	--- APPLIED PHYSICS LETTERS, vol. 65, no. 5, 1 August 1994, NEW YORK US, pages 645-647, XP000570879 D.R SMITH ET AL: "Experimental and theoretical results for a two-dimensional metal photonic band gap cavity" see page 645, left-hand column, paragraph 2 -----	1,6,7,9, 12-14,17

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No

PCT/US 96/01903

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US-A-5187461	16-02-93	AU-B- 1435192	15-09-92
		WO-A- 9215124	03-09-92
		US-A- 5471180	28-11-95
		US-A- 5389943	14-02-95

WO-A-9416345	21-07-94	CA-A- 2153485	21-07-94
		EP-A- 0678196	25-10-95

**This Page is Inserted by IFW Indexing and Scanning
Operations and is not part of the Official Record**

BEST AVAILABLE IMAGES

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images include but are not limited to the items checked:

☐ **BLACK BORDERS**

☒ **IMAGE CUT OFF AT TOP, BOTTOM OR SIDES**

☒ **FADED TEXT OR DRAWING**

☐ **BLURRED OR ILLEGIBLE TEXT OR DRAWING**

☐ **SKEWED/SLANTED IMAGES**

☐ **COLOR OR BLACK AND WHITE PHOTOGRAPHS**

☐ **GRAY SCALE DOCUMENTS**

☐ **LINES OR MARKS ON ORIGINAL DOCUMENT**

☐ **REFERENCE(S) OR EXHIBIT(S) SUBMITTED ARE POOR QUALITY**

☐ **OTHER:** _____

IMAGES ARE BEST AVAILABLE COPY.

As rescanning these documents will not correct the image problems checked, please do not report these problems to the IFW Image Problem Mailbox.

THIS PAGE BLANK (USPTO)